

When severe convective weather requires rerouting aircraft, FAA traffic managers employ severe weather avoidance plans (e.g., Playbook routes, Coded Departure Routes, etc.) These routes provide pilots with safe paths around weather-affected regions, and provide controllers with predictable, and often well-established flight plans. However, they often introduce large deviations to the nominal flight plans, which may not be necessary as weather conditions change. If and when the imposed traffic management initiatives (TMIs) become stale, updated shorter path flight trajectories may be found en route, providing significant time-savings to the affected flights. Multiple Flight Common Routes (MFCR) is a concept that allows multiple flights that are within a specified proximity or region, to receive updated shorter flight plans in an operationally efficient manner. MFCR is believed to provide benefits to the National Airspace System (NAS) by allowing traffic managers to update several flight plans of en route aircraft simultaneously, reducing operational workload within the TMUs of all affected ARTCCs. This paper will explore some aspects of the MFCR concept by analyzing multiple flights that have been selected for rerouting by the NAS Constraint Evaluation and Notification Tool (NASCENT). Various methods of grouping aircraft with common or similar routes will be presented, along with a comparison of the efficacy of these methods.

Analysis of Multi-Flight Common Routes for Traffic Flow Management

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This paper presents an approach for creating common weather avoidance reroutes for multiple flights and the associated benefits analysis, which is an extension of the single flight advisories generated using the Dynamic Weather Routes (DWR) concept. These multiple flight advisories are implemented in the National Airspace System (NAS) Constraint Evaluation and Notification Tool (NASCENT), a nation-wide simulation environment to generate time- and fuel-saving alternate routes for flights during severe weather events. These single flight advisories are clustered together in the same Center by considering parameters such as a common return capture fix. The clustering helps propose routes called, Multi-Flight Common Routes (MFCR), that avoid weather and other airspace constraints, and save time and fuel. It is expected that these routes would also provide lower workload for traffic managers and controllers since a common route is found for several flights, and presumably the route clearances would be easier and faster. This study was based on 30-days in 2014 and 2015 each, which had most delays attributed to convective weather. The results indicate that many opportunities exist where individual flight routes can be clustered to fly along a common route to save a significant amount of time and fuel, and potentially reducing the amount of coordination needed.

I. Introduction

WEATHER was responsible for about 80,000 delayed flights during March through September of 2014 and 2015 each in the National Airspace System (NAS)¹. When severe convective weather affects air traffic, FAA traffic managers employ severe weather avoidance routes (e.g., Playbook routes, Coded Departure Routes). These routes provide pilots with safe paths around weather-affected regions, and provide controllers and dispatchers with predictable, well-established flight plans. However, they often introduce large deviations to the nominal flight plans, which may not be necessary as weather conditions change. Automation to alert traffic managers to indicate that the imposed avoidance routes may not be necessary is not available today.

If and when the imposed reroutes and associated Traffic Management Initiatives (TMIs) become stale, updated shorter path flight trajectories may be found en route, providing significant time savings to the affected flights. Dynamic Weather Routes (DWR)² is a concept that allows a flight to request a shorter flight using current day operational procedures. DWR demonstrated that it can provide benefits to the NAS^{3,4} by allowing flight operators to update flight plans of en route aircraft to save time and fuel (Patent Ref. 12). The concept also reduces overall

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sector congestion which can help FAA operations and controller workload. The concept, however, employed proposed changes to individual flights. Other research^{5,6} presents design trade-offs for strategic flow planning strategies to manage multiple flights. The approach employed by Taylor, Wanke, et al. is for flights that have weather forecasted on their current flight plan, and creating an avoidance route. It differs from this research because here the flights are grouped together by finding shorter paths due to inefficient weather avoidance routes or removing a stale avoidance route. Their strategies could be employed for single or multiple flights, and their studies consider various constraints in the airspace and the imposed TMIs. In another research⁷, Evans, et al. looked at improving operational acceptability of DWR by analyzing commonly used routes. Historical flight routes were analyzed for better DWR solutions for Fort Worth Center.

This paper explores aspects of employing the savings potential of single flights in the DWR concept to multiple flights on a common route. The proposal is to design a common route (or utilize routes from Ref. 7) for multiple flights based on the time and fuel saving potential already assessed by DWR. The NAS Constraint Evaluation and Notification Tool (NASCENT)^{8,9} is a NAS-based automation system which implements the DWR concept for all 20 Centers in the NAS (Patent Ref. 13). Using individual flight advisories identified by NASCENT, methods of grouping aircraft with common or similar routes are presented, along with a comparison of the efficacy of advising single flight reroutes and grouping aircraft on common routes.

II. Background

Multi-Flight Common Route (MFCR) is a concept built within the NASCENT tool, which has its origins with the DWR concept. Described in detail in Ref. 1, DWR has been installed at the American Airlines' (AAL) Operations Center in Fort Worth, TX. It finds an alternate shorter-path flight plan while within the Fort Worth (ZFW) Air Route Traffic Control Center (ARTCC or Center). The suggested route would safely avoid convective weather without overloading traversed sectors, and indicates if the flight is affected by a required reroute TMI. Figure 1 illustrates this concept. Here, the current active flight plan (shown in light blue), which was designed to avoid the convective weather, adds a significant amount of travel time for the flight. The DWR system finds a shorter route using the following process. First, a reference route from the current position to the last fix on the flight plan within a limit rectangle (drawn about 200 nmi from latitude and longitude extrema of the Center boundary) is created (reference flight plan route shown dotted in Fig. 1). If there is weather forecasted along this reference route, an avoidance route is calculated, with at most two auxiliary waypoints (shown as Dynamic Weather Route in dark blue with one auxiliary waypoint in green). If there is no weather along the reference route, it becomes the DWR advised route. If this new route has a minimum of 5 minutes (or a user-specified number of minutes) of wind-corrected flying time savings, it is proposed to the ATC Coordinator at American Airlines. He or she would be notified through an audible tone, and would then alert the flight dispatcher responsible for the flight.

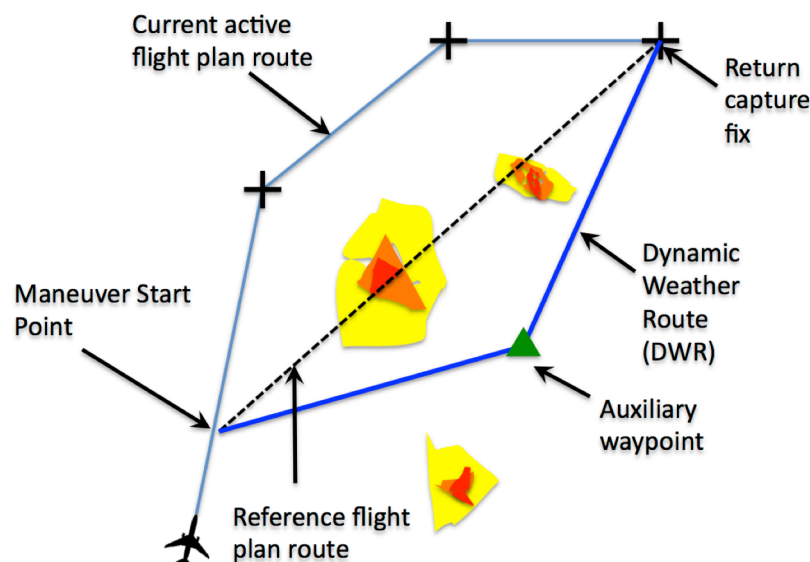


Figure 1. Single flight dynamic weather route concept schematic

vision for MFCR is to apply the common route solution to several en route aircraft together, alert the traffic manager, and provide updated flight plans to all affected aircraft simultaneously via ABRR, when deemed acceptable.

III. Approach

The MFCR analysis begins by running NASCENT (within NASA’s Future ATM Concepts Evaluation Tool-FACET¹⁰ system) with historical data. Historical flight data are used, along with convective weather data (for determining valid weather-free flight plans) and wind data (for computing flight times). NASCENT uses the one-minute update Traffic Flow Management System (TFMS) data feed for flight data. It uses the Convective Weather Avoidance Model (CWAM)¹¹ weather data, which are derived from the Corridor Integrated Weather System (CIWS) data from MIT Lincoln Labs. CWAM altitude-based polygons represent a model of the pilot deviation around convective weather and are used by the avoidance algorithm in NASCENT. It also uses the hourly Rapid Refresh wind data from the National Oceanic and Atmospheric Administration (NOAA). The wind data are used for trajectory generation and time savings computation. NASCENT records all flights that it determines can be rerouted to save at least five (or a user-configurable number of) minutes saved. If it finds at least three (or a user-configurable number of) flights that share a predetermined set of attributes (described next) MFCR identifies this “cluster” of flights along with a common route they could fly on, and computes a total flight time savings for all flights in the cluster.

The cluster definition considers various parameters:

- the current Center the aircraft is in,
- the proposed return capture fix for NASCENT (reference or avoidance) route,
- the origin or destination airport,
- the origin or destination Center, and
- the auxiliary waypoints (if) added for the avoidance route.

Many combinations of these parameters were considered for cluster computation, i.e., flights in current Center going to a particular destination airport, etc. The flights’ current Center was used in all clusters due to operational control considerations. By studying various combinations, it was found that most clusters (with associated large potential time savings for MFCR) were observed when flights in current Center were grouped going to the same return capture fix. However, some of the other combinations also yielded significant clusters for specific Centers. In all, six different groupings were considered as most likely from assessing several days of data. The combinations and the corresponding Centers are provided in Table 1 below. In that table, the first row represents clusters that were formed with flights that were in the same Center (CurrCenter) going to the same destination Center (DestCenter) via the same auxiliary waypoint (AuxWypt). RetCapFix and DestArpt refer to the return capture fix and the destination airport. Therefore, the fourth row represents clusters formed with flights in the same Center going to the same destination airport through the same return capture fix. It was observed that large number of clusters were found commonly in Fort Worth (ZFW), Denver (ZDV), Houston (ZHU), and Miami (ZMA) Centers (see Table 1). Memphis (ZME), Minneapolis (ZMP), Salt Lake (ZLC), and Kansas City (ZKC) Centers also showed significant clusters. The number of clusters observed varied significantly with the location of weather on the particular day. Some more discussion is presented in the Results Section and in Fig. 3.

Table 1: MFCR cluster criteria and Centers with most clusters.

Clustering criteria	Centers with most clusters
CurrCenter-AuxWypt-DestCenter	ZFW, ZDV, ZHU, ZMA, ZME
CurrCenter-AuxWypt	ZFW, ZDV, ZHU, ZMA, ZMP, ZLC, ZME, ZKC
CurrCenter-DestCenter	ZFW, ZDV, ZHU, ZMA
CurrCenter-RetCapFix-DestArpt	ZFW, ZDV, ZHU, ZMA, ZMP
CurrCenter-RetCapFix	ZFW, ZDV, ZHU, ZMA, ZMP, ZLC
CurrCenter-DestArpt	ZFW, ZDV, ZHU, ZMA, ZMP, ZLC

By comparing the performance of the MFCR algorithm on historical data, especially among days with significant convective weather-induced delays, a viable and efficient clustering method (as described above) can be determined. Furthermore, if MFCR identifies flight clusters in a specific region with a high enough frequency, it suggests a potential new reusable common route, perhaps a newly designed Playbook route, corresponding to the flight routes within those clusters.

IV. Results

A. Scenario Days

At this point in the investigation, historical runs of NASCENT have focused on 60 days significant convective weather activity. These days were highest delay days with convective weather as the main cause of delay during March through October of 2014 and 2015. For 2014, 30 days of data used for this study are from April, 3, 15, 29, 30, May 9, 15, 16, 27, 28, June 5, 9, 11, 12, 13, 18, 19, 23, 25, July 2, 3, 8, 9, 13, 14, 15, 23, 27, 28, September 6, and October 2. Similarly, 30 days were selected in 2015 as well. They are from March 23, 26, April, 9, 10, 20, May 11, 18, 19, 27, 31, June 1, 2, 8, 15, 16, 17, 23, July 9, 14, 18, 21, 30, August 11, 20, September 10, 30, and October, 1, 2, 9, 28. In 2014, for individual flights, the combined maximum savings were observed on October 2 and combined minimum savings were observed on May 16. In 2015, those days were April 10 and September 30. October 2, 2014 and April 10, 2015 were high-delay days due to significant convective weather throughout the central United States. On those two days in 2014 and 2015, with a minimum time-savings of 5 minutes, NASCENT presented advisories for 1262 and 615 individual flights with potential total savings of 11,283 and 4,915 minutes with a potential total fuel savings of 819,216 and 382,640 lbs., respectively. For the 30-days of data in 2014, NASCENT suggested single-flight advisories for 13,273 flights with potential time savings of 121,625 minutes with a potential fuel savings of 7,517,448 lbs. For 2015, those numbers are 10191 flights, 83,325 minutes, and 5,994,494 lbs. of fuel. For all the results, the advised route maneuver start point of 5 minutes from the current position to account for dispatcher-pilot-controller coordination.

B. Formation of Clusters

For MFCR calculations, NASCENT is set to identify individual flights that have at least 2 minutes of flight time saving by finding an alternate flight plan segment to a return capture fix (with or without an auxiliary waypoint) for flights currently in the same Center (second last row in Table 1). The MFCR module is set to find clusters of at least 3 flights within the NASCENT list of flights that share this criterion (CurrCenter-RetCapFix) for clustering. Figure 3 shows the results organized by Center for October 2, 2014. While all 20 Centers were run in simulation, only those with significant number of clusters are shown here. Time is on the horizontal axis, with the capture fix index on the vertical. For example, examining Fort Worth Center (ZFW), the most used fixes (along the vertical axis) were Springfield, MO (SGF), Grand Junction, CO (JNC), Fort Stockton, TX (FST), and Newman, TX (EWM). The vertical axis represents an index for each fix, instead of the name of the fix because there are too many identified return capture fixes. The size of the circular plot markers indicates the relative population of the cluster. Each circular marker on these plots indicates that MFCR was able to find a cluster of 3 flights with at least 2 minutes of potential flight time savings per flight. For example, in Denver Center (ZDV) from about 15:00 UTC to the end of the day, MFCR identified many clusters of flights on common routes as indicated by the long line of circles sharing the same capture fix in the ZDV plot of Fig. 3 (top left).

Once these clusters are found, the auxiliary waypoint selection process is implemented to find a common route. In this process, each flight is simulated to fly through every other flights' auxiliary waypoint (if one exists) and the total savings (greedy optimization) for each route from all combinations are computed. The maximum-savings common route is selected as the common route for that cluster (the MFCR). It was observed that overall for the 2014 and 2015 data, 92% of the savings value was captured by MFCRs from its constituent individual flights. The process of common route selection from individual flights is responsible for the 8% loss (more in Table 2 below). It should be noted that at every one-minute time step, MFCR records a potential multi-flight common route that may contain some or all of the flights of an earlier clustered reroute solution (with updated potential time savings). Thus, not all the plot markers in a string of clusters contain unique flights. However, long strings of MFCR solutions like those in the ZDV plot or the ZID plot (from 12:30 - 22:45 UTC) suggest that the existing TMI routing might be stale, since NASCENT is able to propose shorter path flight plans for many flights in the region over a long duration of time. Looking at the 15:00 - 23:59 UTC time period in Denver Center, Fig. 4 (top) shows the duration of time for flights that NASCENT identified with potential flight time savings of at least 2 minutes. The colors of lines have no meaning but used for distinguishing different flights. NASCENT found a reroute for all these flights that ended in a return capture fix of MCW (Mason City) in northern Iowa. All these flights were east-bound with a destination of Chicago O'Hare International Airport. During this time, the WEST_TO_ORD required reroute advisory was valid

from 1000 UTC on October 2 to 0200 UTC on October 3. It was determined from observation of actual data that the weather had moved away from MCW around 1800 UTC on October 2.

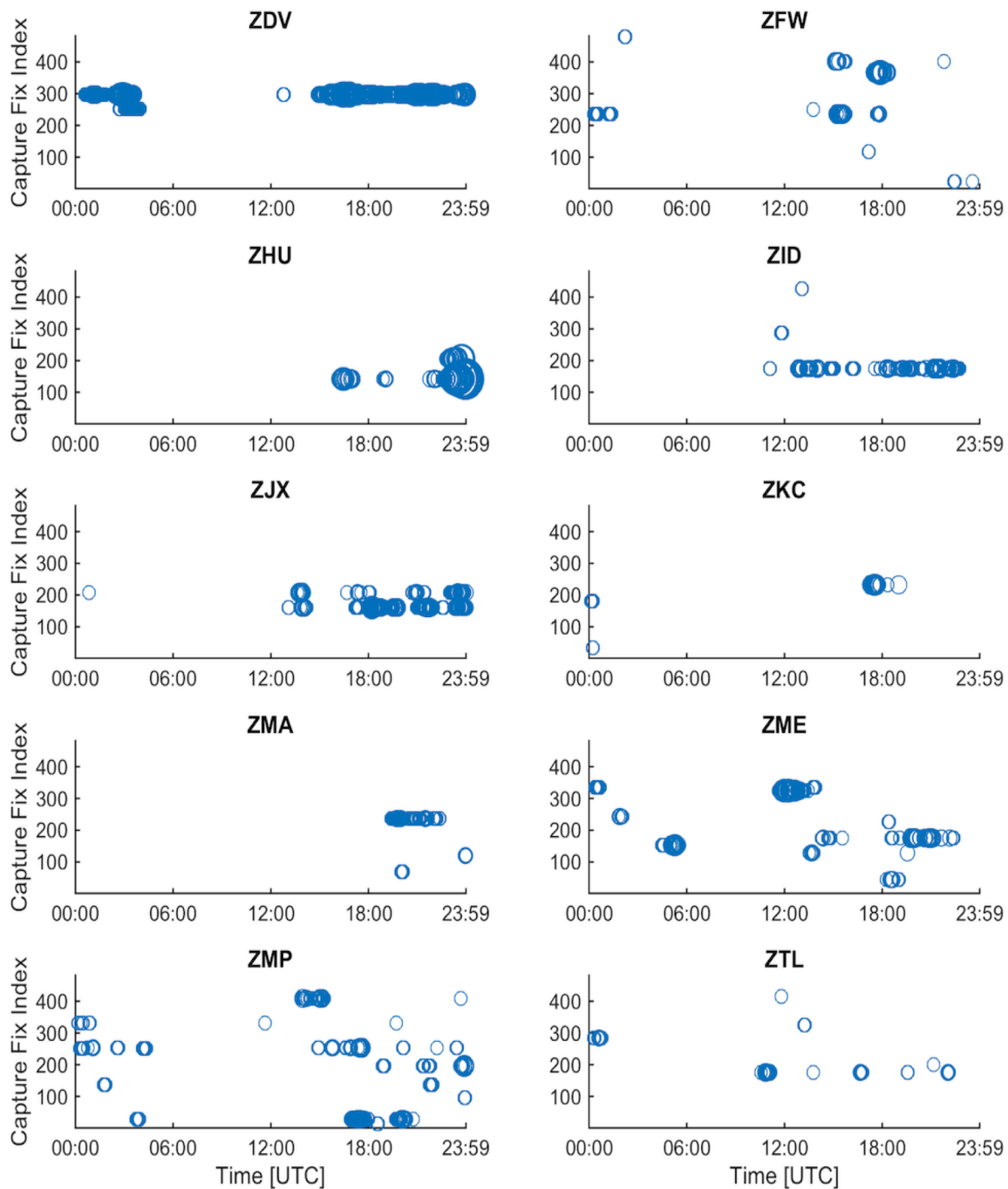
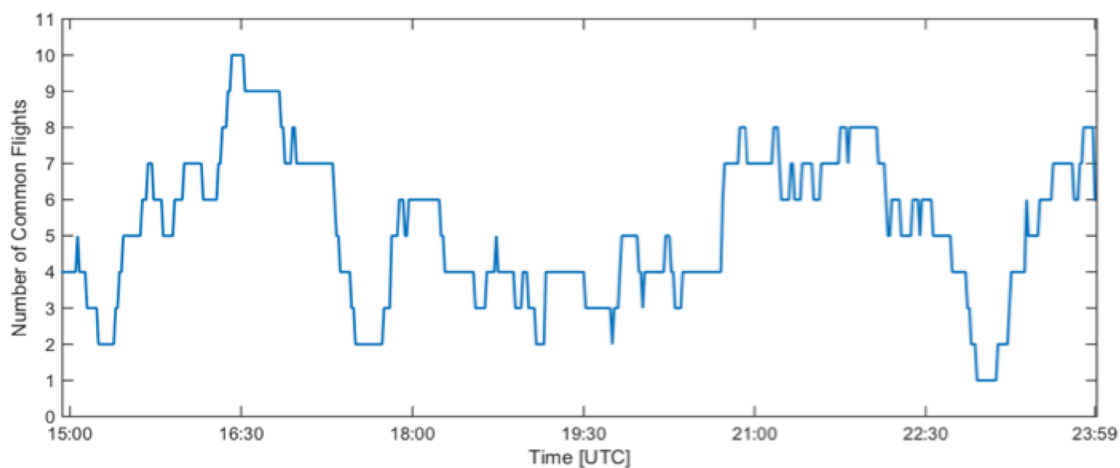


Figure 3: MFCR Clusters for October 2, 2014. Clustered by current center and return capture fix. From top (left to right) are Denver, Fort Worth, Houston, Indianapolis, Jacksonville, Kansas City, Miami, Memphis, Minneapolis, and Atlanta Centers.

Figure 1 is a Gantt chart illustrating the flight schedule of the 100 busiest airlines in the US in 2019. The horizontal axis represents time in UTC, ranging from 15:00 to 23:59. The vertical axis represents the number of flights. Each horizontal line represents a flight route, with the airline code and flight number labeled at the end. The chart shows a high density of flights, particularly between 18:00 and 22:00 UTC. The flight routes are color-coded by airline, and the chart includes a legend for the airlines.



If single-flight and multi-flight routes were computed during this time span for the collection of flights shown in Fig. 4, the total flight time savings would amount to roughly 160 minutes. This calculation is performed in a causal way by the following method: At each time step, if NASCENT identifies at least three flights that have not already been selected by MFCR in an earlier cluster, assume these new flights will be clustered as a new group and sum

their individual flight time savings. Adding up all the individual flight time savings for every time step during this period leads to the final savings value. Clearly, some time-savings benefit is lost due to this approach.

C. Cluster Groups and Time Savings

Table 2 presents a summary of the flights, clusters, savings for the top-30 most delay days in 2014 and 2015. All of these values are with a maneuver start point of 5 minutes from current position, and with NASCENT advisories with minimum 5-minute savings.

Table 2: Number of flights in single- and multi-flight advisories and the potential time savings.

	2014 – 30 days	2014, October 2	2015 – 30 days	2015, April 10
Total single flights	13273	1262	10191	615
Total savings (min.)	121625	11283	83325	4915
Flights in clusters	1123	242	771	124
Number of clusters	273	57	203	27
MFCR savings (min.)	8767	1976	6024	995
MFCR/Total savings	0.07	0.18	0.07	0.20

From Table 2, it's seen that the 30-day average savings from 2014 and 2015 obtained by MFCR compared to individual NASCENT advisories (last row in Table 2) is about 7%. For the high-delay days of October 2, 2014 and April 20, 2015, they were 18% and 20%, respectively. The small percentages are due to the inability to form more clusters using this method and the auxiliary waypoint selection process. However, as mentioned earlier, the MFCRs capture 92% of the constituent individual flight advisory savings. Therefore, the benefit of reduced traffic manager workload from coordinating several flights on separate routes to a single route comes with a loss of 8% loss of time savings.

One of the metrics of interest is the frequency of development of these clusters. Figures 5 and 6 address that question. Figure 5 presents the number of clusters formed and Fig. 6 presents the corresponding total time savings during each hour of the day for various minimum potential time savings required for individual flights. Since October 2, 2014 was a high-delay day, it was analyzed for this purpose. On that day, we see from Table 2 that 57 unique clusters were formed that comprised of 242 flights (green line).

Based on the discussion above and Fig. 5 below, it is observed that during 23:00 to 23:59 on October 2, 2014, over 18 unique clusters (rightmost red marker) were found comprising of 3 or more flights with a minimum potential savings of 2 minutes. From Fig. 6, it is observed that the potential time savings just for that hour could be about 330 minutes. It is also observed from the two figures that as the minimum potential time savings required for a flight to be posted on the NASCENT list is increased, the number of clusters formed fall off. The clusters reduce from 18 to 13, 8, and 4 for minimum time savings of 2, 3, 5, and 10 minutes, respectively. Similarly, the time-savings values shown in Fig. 6 fall off from 330 minutes to 320, 240, 130 minutes, respectively. This fall off is due to fewer flight advisories being found by NASCENT as the required minimum time savings increases. Also, it should be noted that the group count numbers representing 2-minute savings (Fig. 5, red line) cannot be below the line for 3-minute savings (blue line), which cannot be below the 5-minute savings (green line), and so on; because the larger time-savings group-counts are subsets of the smaller time-saving equivalents. However, that is not necessary for the potential time savings line representing 2-minute savings. It can be observed that at 13 UTC, in Fig. 6, the red marker is below the blue and green markers. This is because the group or cluster constituents could be different with different time savings, if the common route solution does not work for some member flights.

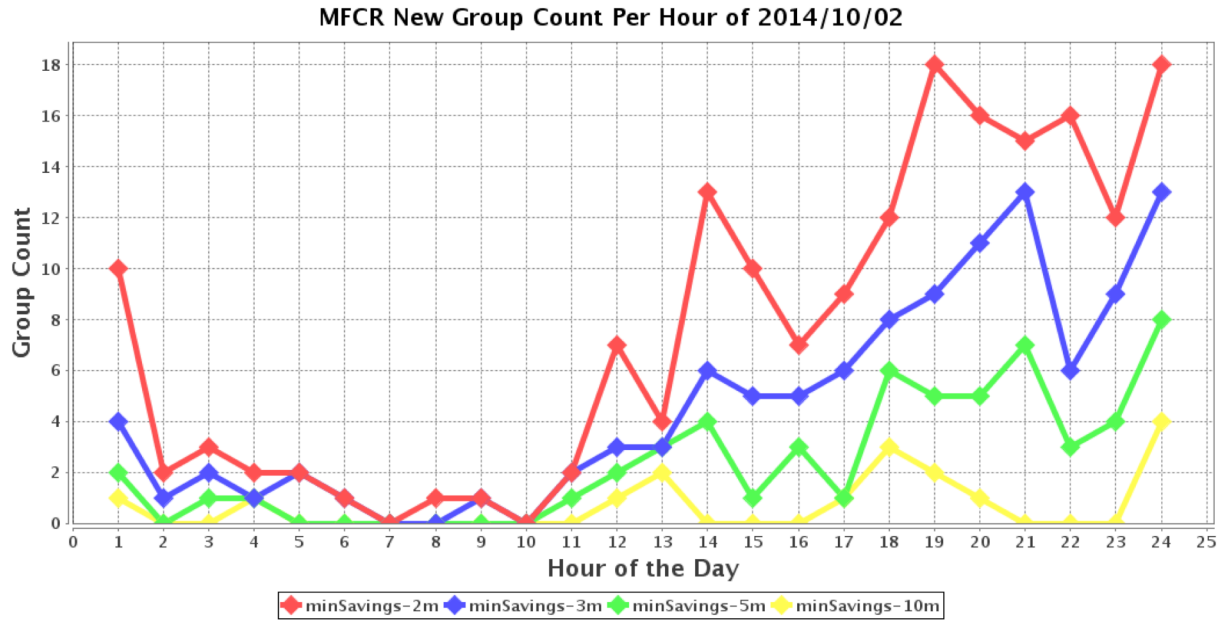


Figure 5. MFCR unique flight groups as a function of time of day, with various curves representing the minimum savings specified per flight for NASCENT advisories.

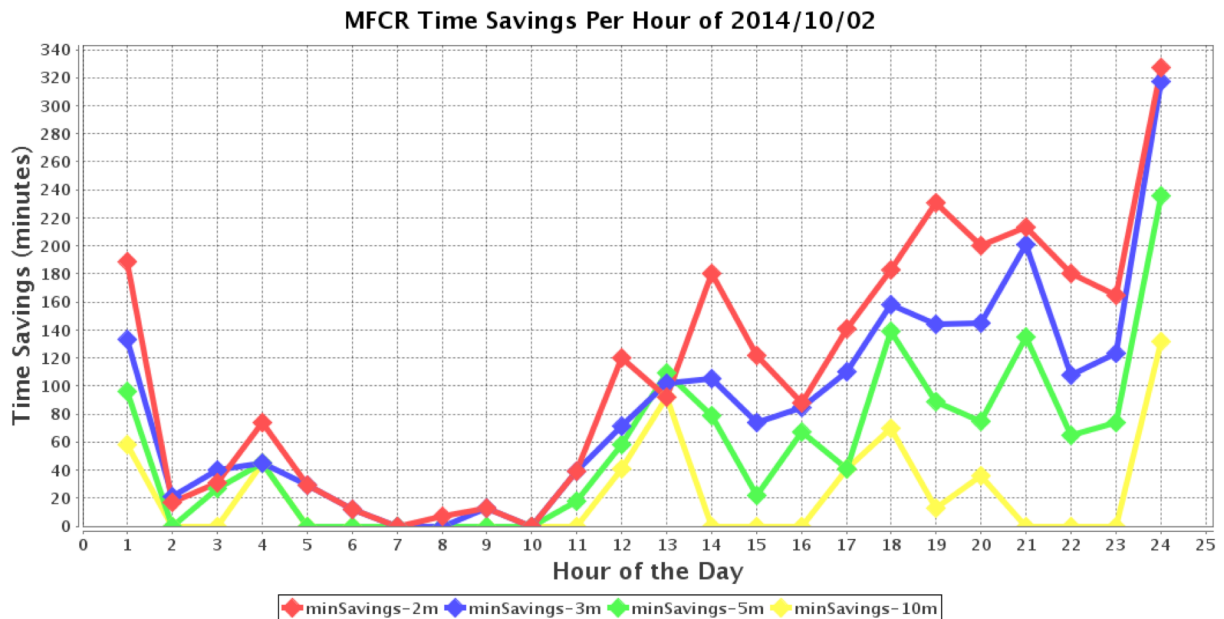


Figure 6. MFCR unique flight group's potential time savings as a function of time of day, with various curves representing the minimum savings specified per flight for NASCENT advisories.

D. Large Cluster Formation

Figure 7 displays an instance of 14 flights in a cluster in Fort Worth Center flying from east to west. Notice that the bottom window displays the MFCR details. It shows that for the 14 flights, a total savings of 144 minutes could be obtained, if all these flights were to fly on the proposed common route. The suggested route is for each flight to go from the current position to the return capture fix El Paso, TX, (ELP) via the auxiliary waypoint Gooch Springs,

TX (AGJ), with rest of the route unchanged. From the sector congestion windows shown in Fig. 8, it is apparent that by flying the new route, a large sector that was red (Houston Center high altitude sector ZHU98) has been circumvented, with no additional congestion created. The common route avoids ZHU98 and goes to the north of it through Ft. Worth Center high altitude sector ZFW82. The capacity of that sector is 18 and it's not predicted to be congested.

From the top main window of Fig. 7, it is observed that the weather is to the north of this route and data showed that it was moving to the northeast. The playbook route clearly was not necessary at this point in time. With the use of the proposed MFCR, a significant saving could be achieved.

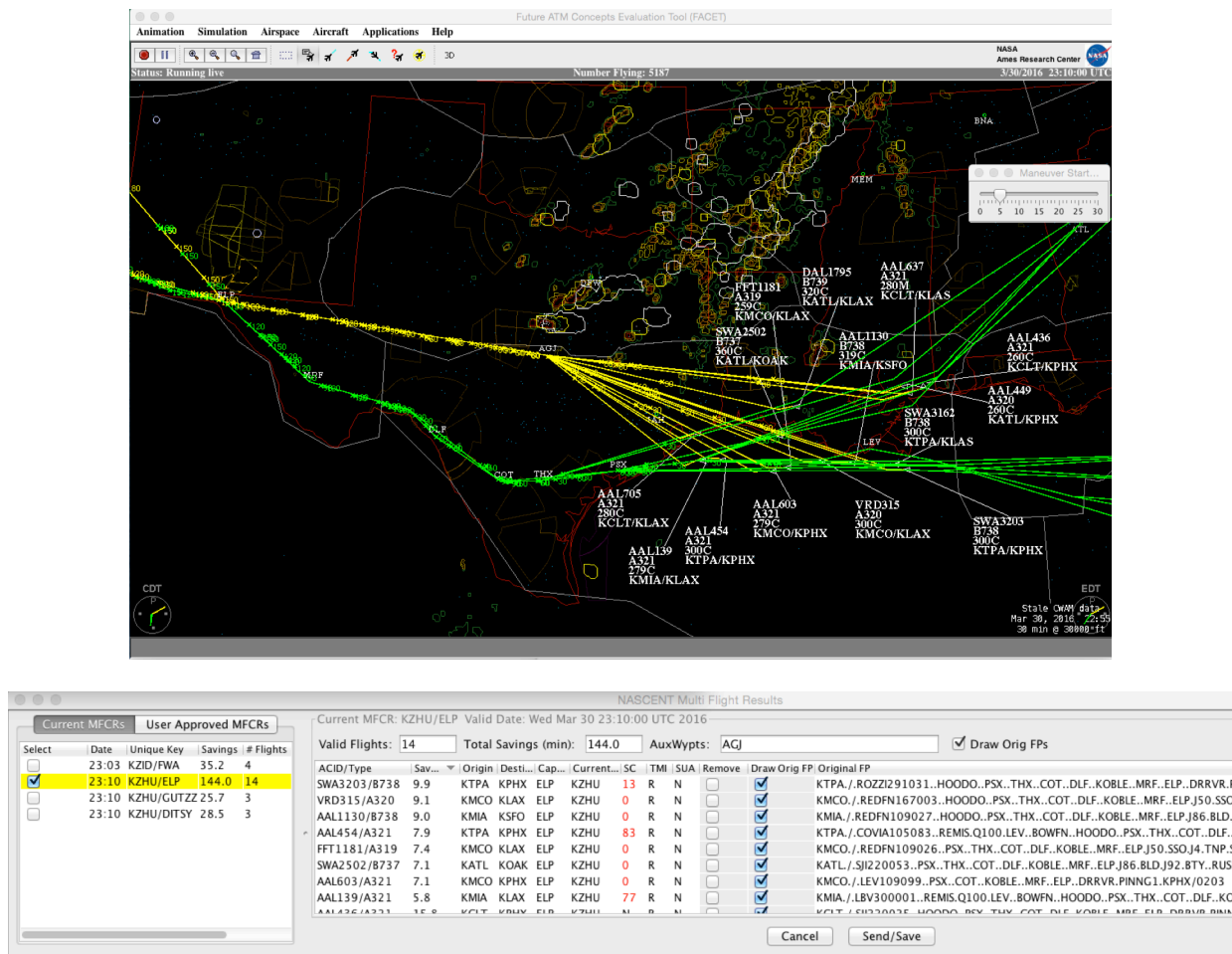


Figure 7. Display of NASCENT with 14 flights in a cluster in Fort Worth Center and the suggested common route (top). Clusters of flights with the number of flights in the cluster, savings and auxiliary waypoint (AGJ) shown in the bottom window.

E. Discussion

It is worth noting three aspects at this point. First, whether the proposed MFCR is selected for implementation or not, the goal is to bring the opportunity of possible time savings and reduced sector congestion to the attention of the decision makers at the FAA traffic management unit and the flight operator facility. Second, the example showed in Fig. 7 started as a cluster of 4 member flights, which increased to 14 flights (as displayed in the figure) and ended up being a cluster of 21 flights. The dynamic nature of flights being added to the cluster as time goes by, could be used for efficient traffic management, either by using the same proposed route (as in a Playbook route) or in disparate groups (locally defined regional routes), as the traffic conditions dictate. Lastly, it was learned during conversations

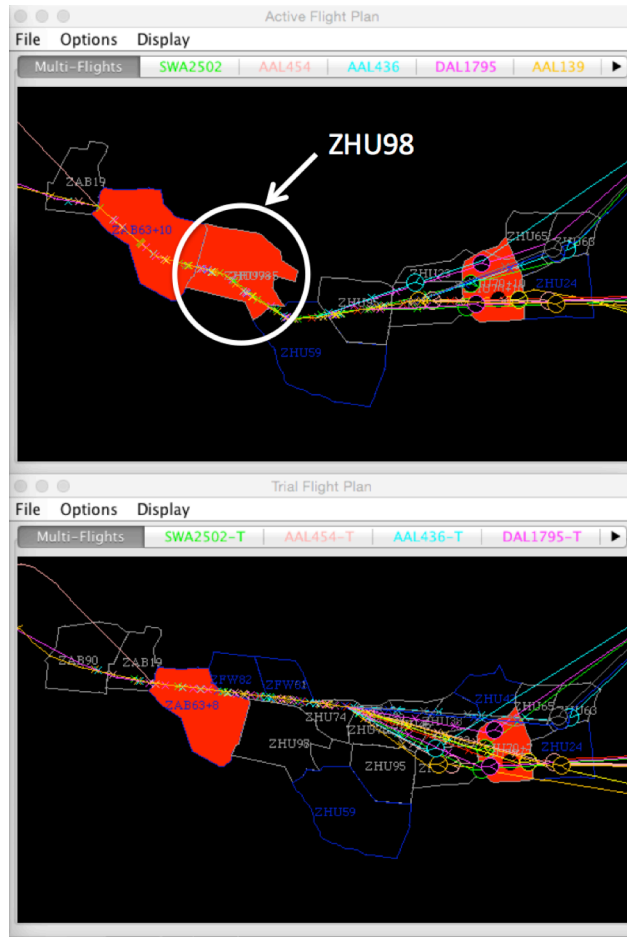


Figure 8. Sector congestion windows with 14 flights (shown in Fig. 7) along their original routes (top) and along the multi-flight common route in Fort Worth Center. Notice the clustering bypasses Houston Center high altitude sector (ZHU98) altogether, reducing its congestion.

with FAA traffic managers that the soon to be deployed AirBorne ReRouting (ABRR) technology could benefit from the MFCR concept and its implementation. It serves two purposes. First, with the ABRR mechanism in place, it could serve to reduce the coordination time (with area supervisors, and then in turn with traffic controllers) significantly lowering their workload for acceptable reroutes that reduce sector congestion. Second, traffic managers (who are already busy during severe weather events) would be alerted to opportunities and would not have to search for reroute options since MFCR would propose a time-saving workable solution to them.

The MFCR results presented herein have used current Center and common return capture fix as the criterion of clustering flights for rerouting. From Table 2, it was seen that the 60-day savings obtained by MFCR compared to individual NASCENT advisories (last row in Table 2) is about 7%. The small percentages are due to the inability to form more flight clusters using this method and the auxiliary waypoint selection process. Other methods to find common routes for flights, beyond the parameters presented here, are possible. These include clustering based on not just grouping flights with a certain amount of minimum potential time savings. An example is where several flights that have weather intersecting their current route. This is similar to the approach selected in Refs. 5 and 6. Implementing a preliminary version of that algorithm to cluster flights based on detected weather on current path, it was found that for October 2, 2014, there were 2529 flights which could be clustered together. However, these clusters avoid weather and therefore introduce delay. Note that from Table 2 above, the number of NASCENT flights for current research is 1262.

Other more nuanced grouping methods involving time and location may arise as the current research continues. As these various clustering methods are tried, means of evaluating their performance will be similar to the above. Also, by finding extended periods of time with multiple NASCENT/MFCR alerts (like shown in Fig. 4), the authors believe that this analysis will identify regions that could benefit from playbook route alterations, or the creation of new ones. The routes generated by NASCENT in those regions could even be used to synthesize these routes. The extension of this idea has been proposed by several traffic managers, who have suggested utilizing the proposed common routes to create a dynamic Playbook route or design a new Playbook route altogether. There are several traffic manager evaluations and human-in-the-loop simulations planned during the fall of 2016 when such notions of dynamic weather avoidance routes and dynamic clusters will be explored. Currently, an estimate of the workload is not available and the assessment will be conducted during the evaluations and simulations. The experts will provide ratings for level of difficulty of handling single and multiple flight scenarios and the amount of inter-Center coordination required.

V. Concluding Remarks

Previous work has shown that modifying the route of individual aircraft can provide benefits to improving flight efficiency in the NAS by taking advantage of inefficient weather routes. By rerouting aircraft in real time to reduce excessive flight distances around weather that may have dissipated in a region, DWR and NASCENT can provide measurable time and fuel savings to flight operators across all 20 Centers. MFCR is an extension of DWR implementation in NASCENT that proposes reroutes to be implemented in a group, rather than individually. By doing so, operational workload is presumably reduced for the FAA traffic managers, and so is the possibility of neglecting individual flight (NASCENT) alerts. This paper presents the performance of NASCENT/MFCR and proposes various techniques that MFCR may use to implement clustering of flights to fly on common routes.

On a significant weather activity day of October 2, 2014, this analysis showed about 330 minutes of potential time savings with 18 clusters in just one hour. Overall, results for individual flight potential savings and multiple flights flying on common routes were presented for the 60-days data with 30 days in 2014 and 2015 each. It was found that MFCRs captured about 7% of the savings computed for all single flight advisories. It was also found that on an average, MFCRs captured about 92% of potential savings of the constituent individual flights. Furthermore, it was identified that various Centers could capture different number of clusters based on the location of weather and existing traffic conditions. A cluster that grew from 4 flights to 14 flights was shown, which later grew to 21 constituent flights. During the course of this work, it was highlighted that the historical simulations and analysis may highlight new routes which could be created, leading to a new line of future research for dynamic Playbook routes or creation of new Playbook routes altogether.

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